Annual push moraines as climate proxy

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Received 11 June 2009; revised 10 August 2009; accepted 3 September 2009; published 22 October 2009.

[1] We reconstruct the terminus position of a mountain glacier in British Columbia, Canada from annual push moraines formed between 1959 and 2007. Our reconstruction represents the longest, annually-resolved record of length change for a North American glacier. Comparison of annual recession with climate records indicates that glacier recession is controlled by air temperatures during the ablation season and accumulation season precipitation during the previous decade. Analysis among records of glacier frontal variation and mass balance in western North America similarly reveals an immediate terminus reaction to summer and net balance and a delayed reaction to winter and net balance. Other mountain ranges may contain long series of push moraines that could be exploited as climate proxies, and to improve understanding of glacier response to climate. **Citation:** Beedle, M. J., B. Menounos, B. H. Luckman, and R. Wheate (2009), Annual push moraines as climate proxy, *Geophys. Res. Lett.*, *36*, L20501, doi:10.1029/2009GL039533.

1. Introduction

[2] Mountain glaciers provide fresh water to millions of people, and contribute to global sea level rise [*Barnett et al.*, 2005; *Meier et al.*, 2007]. Records of glacier terminus fluctuations and mass balance provide insight into how climate affects this important freshwater source. *Meier et al.* [2007] estimate there are 300,000 to 400,000 mountain glaciers and small ice caps on Earth. Length change and mass balance records exist for only 1,800 and 230 glaciers, respectively. Only 39 of these glaciers have records that exceed 30 years in length [*Zemp and van Woerden*, 2008], and there is a strong European bias in these records.

[3] We use push moraines to reconstruct the longest, annually-resolved record of terminus position for a North American glacier. Glaciers form annual push moraines during the accumulation season when forward movement of the glacier snout exceeds ablation, resulting in a seasonal advance [*Bennett*, 2001]. Formation of a push moraine at the glacier margin requires a deformable till sheet. Preservation of annual moraines requires ablation season recession to be greater than advance of the terminus during the following accumulation season. To our knowledge, all studies of annual push moraines are for maritime glaciers with high mass-balance gradients in either Iceland [*Sharp*, 1984; *Boulton*, 1986; *Krüger*, 1995; *Bradwell*, 2004] or Norway [*Andersen and Sollid*, 1971; *Worsley*, 1974].

2. Study Area and Methods

[4] We reconstructed the frontal position of Castle Creek Glacier (53°2′N., 120°24′W., unofficial name), British Columbia (BC), Canada from a continuous series of push moraines that front the glacier (Figure 1). The glacier has an area of 9.4 km^2, a length of 5.85 km, and an elevation range of 2,827 to 1,810 m.

[5] To determine the age of the moraines, we mapped glacier terminus position for 10 dates between 1946 and 2005 from orthorectified aerial photographs (see auxiliary material).[3] We photogrammetrically scanned aerial photograph negatives from the Canadian and BC governments with a ground sampling resolution of $\leq$ 1.0 m. To orthorectify these images, we used common ground control points and the 25 m BC Terrain Resource Information Management Program digital elevation model (DEM). Root mean squared error of these horizontal control points was $\leq$ 1.6 m and typically below 1.0 m. We surveyed push moraines that formed after our latest aerial photographs (2005), and terminus position at the end of the ablation season in 2007 and 2008 with a geodetic-grade global positioning system.

[6] Annual push moraine position indicates a prior maximum glacier extent achieved at the end of the accumulation season, while glacier terminus position is mapped from imagery acquired at the end of the ablation season. Thus, we dated the push moraines immediately down-valley of the known terminus position as being formed at the end of the previous accumulation season. The number of intervening moraines coincides with the years between consecutive images, confirming the annual nature of the moraines. We represent changes in glacier length as the total area between moraines or mapped terminus position divided by the curvilinear width. This method integrates recession across the entire glacier terminus and accounts for retreat along an irregular glacier margin.

[7] To examine the climatic controls on mass changes and related frontal variation, we compared glacier length change records derived from annual push moraines with homogenized climate station records of air temperature and precipitation [*Vincent*, 1998; *Mekis and Hogg*, 1999] from the Prince George, BC climate station, ~180 km to the northwest (Figure 1). For our study, we define ablation season as April – September and accumulation season as October – March. We compared un-lagged and lagged total accumulation season precipitation to assess the role of total accumulation during the following ablation season and a

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0094-8276/09/2009GL039533

[3]Auxiliary materials are available in the HTML. doi:10.1029/2009GL039533.

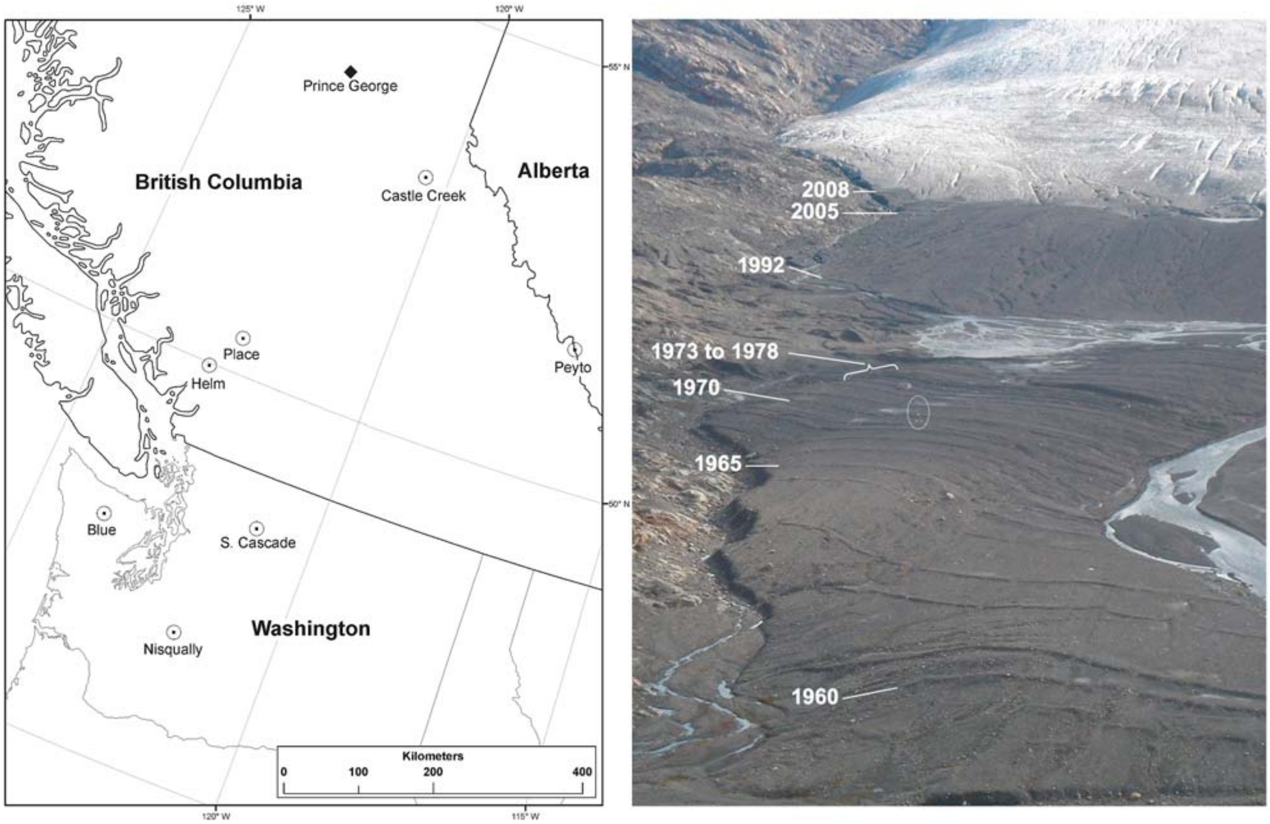

Figure 1. (a) Location of glaciers and climate stations referenced in this paper. (b) Oblique photo of a portion of the Castle Creek Glacier forefield taken 11 September 2008. Dates refer to the year of moraine formation. White circle encloses a 6 m high weather station. Some moraines used in our study are not visible in this photo.

delayed terminus reaction to a precipitation signal integrated over the glacier surface.

[8] To evaluate the representativeness of our length change records derived from annual push moraines, we compared the record from Castle Creek Glacier to net and seasonal mass balance series and glacier length change records from western North America (Table 1). We used cross-correlation analysis to investigate the lagged relation between seasonal (b_w and b_s) and net (b_n) mass balance and frontal variation. *McClung and Armstrong* [1993], *Laumann and Nesje* [2009], and *Winkler et al.* [2009] compared b_n with frontal variation, but we are unaware of previous analysis that considers the relation between frontal behavior and seasonal mass balance.

Table 1. Correlation Table of Western Canada and Pacific Northwest U.S.A. Glacier Frontal Variation and Mass Balance Time Series[a]

	Castle FV[b]	Blue FV[c]	S. Casc. FV[c]	Blue b_n[d]	Helm b_n[c]	Helm b_s[c]	Peyto b_n[e]	Peyto b_s[e]	Place b_n[c]	Place b_s[c]	S. Casc. b_n[f]	S. Casc. b_s[f]
Castle FV[b]		**0.63**	**0.64**	**0.54**	**0.50**	0.44	**0.39**	**0.39**	**0.41**	**0.62**	**0.34**	**0.36**
Blue FV[c]	27		**0.75**	**0.72**	**0.59**	0.23	**0.68**	0.45	0.35	**0.52**	**0.48**	**0.46**
S. Casc. FV[c]	35	22		**0.51**	**0.71**	0.55	**0.41**	0.24	**0.55**	**0.68**	**0.64**	**0.63**
Blue b_n[d]	41	27	34		**0.55**	0.41	**0.45**	**0.37**	**0.56**	**0.53**	**0.43**	**0.42**
Helm b_n[c]	31	17	24	23		**0.89**	**0.59**	**0.58**	**0.73**	**0.80**	**0.60**	**0.66**
Helm b_s[c]	13	12	13	13	13		0.46	0.41	**0.84**	**0.86**	0.55	**0.61**
Peyto b_n[e]	40	19	32	32	29	13		**0.87**	**0.62**	**0.46**	**0.53**	**0.51**
Peyto b_s[e]	37	19	31	32	26	13	37		**0.50**	**0.39**	0.30	**0.53**
Place b_n[c]	43	22	35	35	31	13	40	37		**0.90**	**0.65**	**0.53**
Place b_s[c]	27	19	26	27	15	13	26	26	27		**0.53**	**0.58**
S. Casc. b_n[f]	47	27	35	41	29	13	38	36	41	27		**0.76**
S. Casc. b_s[f]	47	27	35	41	29	13	38	36	41	27	47	

[a]FV is frontal variation; b_s is summer mass balance, and b_n is net mass balance. Bold values indicate significance ($p < 0.05$). Number of paired observations (n) displayed on lower half of table. See auxiliary material for varying years of observation of each time series.
[b]Data from record of frontal variation derived from annual push moraines, this paper.
[c]Data from World Glacier Monitoring Service (http://www.wgms.ch).
[d]Data from University of Washington (http://www.geophys.washington.edu/Surface/Glaciology/projects/blue_glac/blue.html).
[e]Data from *Demuth et al.* [2009].
[f]Data from United States Geological Survey (http://ak.water.usgs.gov/glaciology).

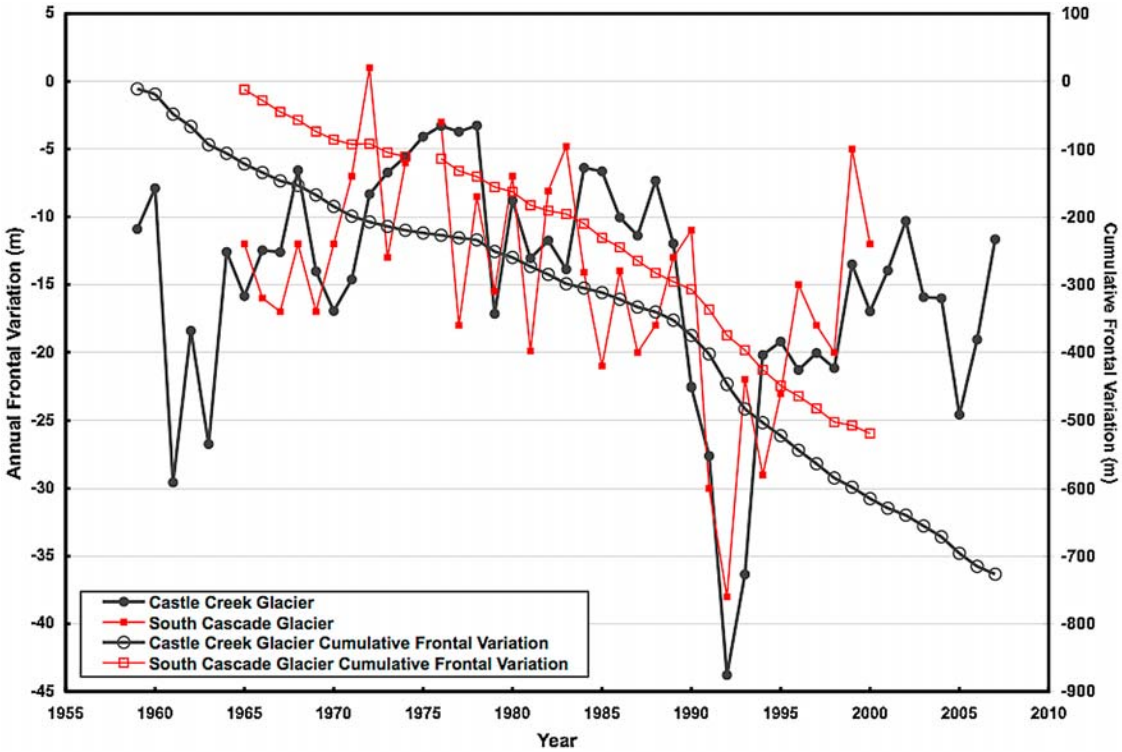

Figure 2. Annual and cumulative frontal variation (1959 to 2007) of Castle Creek Glacier derived from annual push moraines (circles). Annual and cumulative length change of South Cascade Glacier, Washington (squares), are displayed for comparison.

[9] The bed slope near the glacier terminus can affect frontal reaction of a glacier as the position of the terminus depends on ice velocity and the product of bed slope and ablation near the snout [*Nye*, 1965; *Boulton*, 1986]. To investigate the potential role that bed gradient plays as a control of annual glacier length change, we compared the frontal recession for a given year to the average bed slope obtained between two consecutive push moraines. We used two DEMs to assess slope: the 25 m DEM used for image orthorectification, and one derived from about 15,000 points collected with a differential GPS in kinematic mode.

3. Results

3.1. Annual Push Moraines

[10] The forefield contains a continuous series of push moraines that represent the annual terminus position from 1959 to 2007. These deposits sit on low relief till sheets with little intervening bedrock and have been largely protected from fluvial erosion (Figure 1). The height of the push moraines varies from 0.07 – 1.10 m and averages 0.33 m, while moraine width ranges from 0.61 – 4.39 m and averages 1.90 m. These dimensions are similar to push moraines described in Iceland [*Sharp*, 1984; *Boulton*, 1986; *Krüger*, 1995].

3.2. Glacier Length Change

[11] Castle Creek Glacier receded 701 m between 1959 and 2007, averaging 14.3 m a^{-1} with a minimum of 3 to 4 m a^{-1} in the mid- to late-1970s. Recession rates accelerated to over 40 m a^{-1} in the early 1990s (Figure 2). The earliest aerial photographs indicate 185 m of recession between 1946 and 1959, an average rate of 14.2 m a^{-1} that accords with the period 1959–2007. Whereas some glaciers in western North America advanced in the 1960s and 1970s [*Luckman et al.*, 1987], Castle Creek Glacier did not advance in any year since 1959. The slowed recession during the mid-to-late 1970s, however, indicates that this glacier responded to climatic conditions that caused many North American glaciers to advance.

3.3. Relation to Climate

[12] Average ablation season temperature at Prince George correlates with the annual recession from 1959 to 2007 ($r = 0.55$, $p < 0.001$, $n = 49$) indicating that annual glacier length change is partly controlled by summer temperature. There is an inverse relation between annual recession and March precipitation of the current year ($r = -0.42$, $p < 0.01$, $n = 49$). A physical mechanism to account for this correlation is the degree to which late-lying snow can alter the energy balance at the glacier terminus; years of light snow cover during spring lengthen the ablation season and vice versa. Annual recession is correlated to accumulation season precipitation, and this correlation is strongest when precipitation lags terminus response by a decade ($r = -0.38$, $p < 0.01$, $n = 49$). We interpret this delayed reaction of the terminus as the time required for the glacier to begin adjusting its length to changes in upper-elevation mass, which is partly controlled by accumulation season precipitation.

[13] Multiple linear regression reveals that 40% of glacier length change variance is explained by ablation season temperature, March precipitation, and lagged accumulation season precipitation. Ablation season temperature is the

most important model term ($p < 0.001$), followed by March precipitation ($p < 0.01$) and lagged accumulation season precipitation ($p < 0.1$).

[14] Years of extreme recession in the early-1990s (Figure 2) significantly influence the relation between annual glacier fluctuation and climate variables. Omission of the year 1992 in the multiple regression analysis, for example, results in 46% of variance explained, with lagged accumulation season precipitation the most important model term ($p < 0.001$), followed by ablation season temperature ($p < 0.01$), and March precipitation ($p < 0.05$). Removing additional years with anomalously high rates of recession (1991 and 1993) does not further alter the relations.

[15] Residuals from both multiple regression models, however, are autocorrelated, and cumulative departures of these residuals reveal prominent shifts in the late-1970s and late-1980s. Hypothesizing that large-scale atmospheric circulation plays a prominent role in driving annual recession, we used stepwise linear regression with the climate station variables in the previous models, as well as climatic indices that have been shown previously to be important drivers of glacier mass balance in northwest North America [*Rasmussen and Conway*, 2004]. We find annual indices of the Southern Oscillation Index (SOI) [*Trenberth*, 1984] and Pacific Decadal Oscillation (PDO) [*Mantua et al.*, 1997] to correlate with Castle Creek Glacier recession, during the current year and when lagged by a decade. When data from 1992 are included in regression analysis, 45% of annual recession is explained by Prince George March precipitation ($p < 0.01$), annual average PDO lagged 10 years ($p < 0.01$), Prince George summer temperature ($p < 0.05$), annual average PDO ($p < 0.1$), and annual average SOI ($p = 0.1$). When data from 1992 are excluded in regression analysis, 55% of annual recession variance is explained by Prince George accumulation season precipitation lagged 10 years ($p < 0.01$), Prince George March precipitation ($p < 0.01$), annual average PDO ($p < 0.05$), annual average PDO lagged 10 years ($p < 0.05$), Prince George summer temperature ($p < 0.1$), and annual SOI ($p < 0.1$).

3.4. Relation to Other Mass Balance and Frontal Variation Records

[16] The 49-year record accords with frontal variation, b_s, and b_n of glaciers in western Canada and Washington, U.S.A. (Figure 1 and Table 1). Our record correlates with frontal variation of South Cascade and Blue glaciers; both glaciers are over 500 km to the south of Castle Creek Glacier. Interestingly, the recession rates for all three glaciers tripled in the early 1990s (Figure 2; Blue Glacier not shown). Castle Creek Glacier frontal variation correlates with b_s of Peyto, Place, and South Cascade glaciers and is also correlated to b_n of Blue, Helm, Peyto, Place, and South Cascade glaciers (Table 1).

[17] Cross correlation analysis of the Castle Creek Glacier frontal variation record and the b_s record of Place Glacier reveals that both records are correlated at zero lag, while the relation between frontal behavior and b_w is highest when Place Glacier b_w leads the record from Castle Creek Glacier by 13 years (see auxiliary material). A similar pattern is apparent when the frontal variation is compared to Place Glacier b_n, as net balance is the sum of winter and summer balance, revealing both an immediate (zero lag) as well as a lagged relation. This immediate relation between frontal variation and b_s and b_n, and lagged reaction to b_w and b_n is also found for South Cascade Glacier frontal variation and mass balance records, but only an immediate relation exists between Blue Glacier frontal variation and b_n. We find no relation between the length change record and average bed slope angle between moraines from either DEM.

4. Discussion and Conclusions

[18] We show that high-resolution imagery can be used to identify and map annual push moraines in glacier forefields. Series of moraines can be dated, and records of annual glacier length change can be reconstructed when repeat imagery is available. To our knowledge, this study is the first to use push moraines as climate proxies outside of the maritime environments of Iceland or Norway. A preliminary search of glacier forefields in the mountains of western Canada using aerial photographs reveals that annual push moraines are common, but series of moraines that exceed a decade in length are rare. Other mountain ranges, however, may contain long series of push moraines that should be exploited as climate proxies, and to examine glacier response to climate.

[19] *Nye* [1965] concluded that modeling the mass balance history of South Cascade Glacier and Storglaciaren, Sweden, from length change records was unreliable, primarily due to the errors in measuring frontal variation. Records of glacier frontal variation derived from push moraines avoid some of the problems that confront measurements obtained through other methods. Glacier length change measurements from well-preserved series of push moraines allow averaging of recession across much of a terminus and, as push moraines faithfully preserve accumulation season maximum extent, they avoid the problem of measurements that do not coincide with the end of the ablation season.

[20] Summer temperature is an important control of annual length change for Castle Creek Glacier; this finding agrees with previous work on push moraines and glacier length change [*Sharp*, 1984; *Krüger*, 1995; *Bradwell*, 2004; *Sigurdsson et al.*, 2007]. Accumulation season precipitation and b_n also affect annual recession but with a delay that ranges between two to five years [*Salinger et al.*, 1983; *Sigurdsson et al.*, 2007; *Laumann and Nesje*, 2009; *Winkler et al.*, 2009]. For Castle Creek Glacier, we observe that this delay is on the order of a decade

[21] Concordance of Castle Creek Glacier fluctuations with frontal variation, b_s, and b_n of other glaciers in western North America suggests a common climatic driver. Due to the spatial variability of precipitation, it is likely that ablation season temperatures have been the dominant control of glacier recession for these glaciers in recent decades. This conclusion supports the findings that recent glacier recession in western North America and the Northern Hemisphere is primarily caused by anomalously warm temperatures during the ablation season [*Rasmussen and Conway*, 2004]. The synchronous and rapid retreat of Castle Creek, South Cascade, and Blue glaciers in the early 1990s is noteworthy. Regional climatic conditions likely drove this retreat.

[22] Climate, glacier geometry, and ice dynamics all influence the terminus position of alpine glaciers. Our empirical data indicate a delay of about a decade between changes in b_w and the reaction of the Castle Creek Glacier terminus. This delay differs from the theoretical response time of a glacier to approach a new steady state after a change in climate. Response time can be approximated as the quotient of mean ice thickness and the net ablation rate at the terminus [*Jóhannesson et al.*, 1989]. Using area-volume scaling [*Bahr*, 1997] to derive average ice thickness (67 m) and recent measurements of net balance rate at the terminus (-3.4 to -4.0 m a^{-1}), we calculate the response time to be approximately 17–20 years for Castle Creek Glacier. Delay of a decade for accumulation season precipitation defines when the glacier's response to precipitation is maximized, while the method described by *Jóhannesson et al.* [1989] approximates an approach to the end of terminus response; thus maximum terminus reaction to precipitation is delayed by a decade but theoretical response is not achieved for another 10 years. Our analysis indicates glacier termini begin to immediately react to ablation season temperatures and b_s. This reaction is superimposed on a longer frontal reaction which is partly forced by past b_w and filtered by flow dynamics.

[23] Long, continuous records of annual glacier length change form an integral part of regional and global glacier monitoring. Such records can supplement the sparse records of glacier mass balance for remote mountain regions. Annually resolved records of terminus position provide an important dataset to better understand the relation between climate and glacier fluctuations. Measuring seasonal balance and annual frontal variation of the same glacier should be a renewed focus of glacier monitoring as these empirical data provide a means to refine theories proposed for the frontal response time of glaciers.

[24] **Acknowledgments.** We acknowledge the Province of British Columbia and Natural Resources Canada for access to aerial photography. We thank Mike Demuth of the Geological Survey of Canada (GSC) for supplying us with records of Peyto Glacier seasonal mass balance. The comments of Stefan Winkler, an anonymous reviewer, and Editor Eric Rignot significantly improved the manuscript. This work is supported by the Canadian Foundation for Climate and Atmospheric Sciences (CFCAS) as part of the Western Canadian Cryospheric Network (WC^{2}N) and also by the Natural Sciences and Engineering Research Council of Canada (NSERC).

References

Andersen, J. L., and J. L. Sollid (1971), Glacial chronology and glacial geomorphology in the marginal zones of the glaciers, Midtdalsbreen and Nigardsbreen, south Norway, *Norw. J. Geogr.*, *25*, 1–38.

Bahr, D. B. (1997), Global distributions of glacier properties: A stochastic scaling paradigm, *Water Resour. Res.*, *33*, 1669–1679, doi:10.1029/97WR00824.

Barnett, T. P., J. C. Adam, and D. P. Lettenmaier (2005), Potential impacts of a warming climate on water availability in snow-dominated regions, *Nature*, *438*, 303–309, doi:10.1038/nature04141.

Bennett, M. R. (2001), The morphology, structural evolution and significance of push moraines, *Earth Sci. Rev.*, *53*, 197–236, doi:10.1016/S0012-8252(00)00039-8.

Boulton, G. S. (1986), Push-moraines and glacier-contact fans in marine and terrestrial environments, *Sedimentology*, *33*, 677–698, doi:10.1111/j.1365-3091.1986.tb01969.x.

Bradwell, T. (2004), Annual moraines and summer temperatures at Lambatungnajökull, Iceland, *Arct. Alp. Res.*, *36*, 502–508, doi:10.1657/1523-0430(2004)036[0502:AMASTA]2.0.CO;2.

Demuth, M. N., J. Sekerka, and S. Bertollo (2009), Glacier mass balance observations for Peyto Glacier, Alberta, Canada (updated to 2007), in Spatially Referenced Data Set Contribution to the National Glacier-Climate Observing System, State and Evolution of Canada's Glaciers, http://pathways.geosemantica.net/WSHome.aspx?ws=NGP_SECG&locale=en-ca, Geol. Surv. of Can., Ottawa, Ont.

Jóhannesson, T., C. Raymond, and E. Waddington (1989), Time-scale for adjustment of glaciers to changes in mass balance, *J. Glaciol.*, *35*, 355–369.

Krüger, J. (1995), Origin, chronology and climatological significance of annual-moraine ridges at Myrdalsjökull, Iceland, *Holocene*, *5*, 420–427, doi:10.1177/095968369500500404.

Laumann, T., and A. Nesje (2009), A simple method of simulating the future frontal position of Briksdalsbreen, western Norway, *Holocene*, *19*, 221–228, doi:10.1177/0959683608100566.

Luckman, B. H., K. A. Harding, and J. P. Hamilton (1987), Recent glacier advances in the Premier Range, British Columbia, *Can. J. Earth Sci.*, *24*, 1149–1161.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis (1997), A Pacific interdecadal climate oscillation with impacts on salmon production, *Bull. Am. Meteorol. Soc.*, *78*, 1069–1079, doi:10.1175/1520-0477(1997)078<1069:APICOW>2.0.CO;2.

McClung, D. M., and R. L. Armstrong (1993), Temperate glacier time response from field data, *J. Glaciol.*, *39*, 323–326.

Meier, M. F., M. B. Dyurgerov, U. K. Rick, S. O'Neel, T. W. Pfeffer, R. S. Anderson, S. P. Anderson, and A. F. Glazovsky (2007), Glaciers dominate eustatic sea-level rise in the 21st century, *Science*, *317*, 1064–1067, doi:10.1126/science.1143906.

Mekis, É., and W. D. Hogg (1999), Rehabilitation and analysis of Canadian daily precipitation time series, *Atmos. Ocean*, *37*, 53–85.

Nye, J. F. (1965), A numerical method of inferring the budget history of a glacier from its advance and retreat, *J. Glaciol.*, *5*, 589–607.

Rasmussen, L. A., and H. Conway (2004), Climate and glacier variability in western North America, *J. Clim.*, *17*, 1804–1815.

Salinger, M. J., M. J. Heine, and C. J. Burrows (1983), Variations of the Stocking (Te Wae Wae) Glacier, Mount Cook, and climatic relationships, *N. Z. J. Sci.*, *26*, 321–338.

Sharp, M. (1984), Annual moraine ridges at Skállafellsjökull, south-east Iceland, *J. Glaciol.*, *30*, 82–93.

Sigurdsson, O., T. Jónsson, and T. Jóhannesson (2007), Relation between glacier-termini variations and summer temperature in Iceland since 1930, *Ann. Glaciol.*, *46*, 170–176, doi:10.3189/172756407782871611.

Trenberth, K. E. (1984), Signal versus noise in the Southern Oscillation, *Mon. Weather Rev.*, *112*, 326–332, doi:10.1175/1520-0493(1984)112<0326:SVNITS>2.0.CO;2.

Vincent, L. A. (1998), A technique for the identification of inhomogeneities in Canadian temperature series, *J. Clim.*, *11*, 1094–1104, doi:10.1175/1520-0442(1998)011<1094:ATFTIO>2.0.CO;2.

Winkler, S., H. Elvehøy, and A. Nesje (2009), Glacier fluctuations of Jostedalsbreen, western Norway, during the past 20 years: The sensitive response to maritime mountains glaciers, *Holocene*, *19*, 395–414, doi:10.1177/0959683608101390.

Worsley, P. (1974), Recent "annual" moraine ridges at Austre Okstindbreen, Okstindan, north Norway, *J. Glaciol.*, *13*, 265–277.

Zemp, M., and J. van Woerden (Eds.) (2008), *Global Glacier Changes: Facts and Figures*, 88 pp., World Glacier Monit. Serv., Nairobi, Kenya.

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